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3-D Printed Lightweight Microwave Waveguide Devices

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Abstract – This paper provides an overview of five 3-D printed microwave passive circuits operating at frequencies ranging from *X*-band to *W*-band. These circuits were produced from polymers using stereolithography printing and were coated with copper via electroplating. Such polymer-based circuits exhibit significantly reduced weights compared with those made from metal. In addition, 3-D printing offers great flexibility and allows new designs to be constructed. Examples of these novel designs will be described and measurements of some designs will be presented.

Index Terms — Bandpass filter, microwave, spherical cavity resonators, 3-D printing, waveguide.

I. INTRODUCTION

In recent years, 3-D printing (also known as additive manufacturing) has become increasingly popular in the fabrication of microwave passive devices such as waveguide filters and antennas. Plenty of commercially available 3-D printing techniques have been used to fabricate microwave devices as reviewed in [1]. The devices can either be printed from metal powders (e.g. [2]–[3]) or be produced from polymers (e.g., [1], [4]). The latter requires an additional metal-plating process to build a conductive layer on the surface of the structures.

In this paper, advances and challenges of 3-D printing techniques that are suitable for fabricating microwave waveguide devices are discussed. *X*- and *W*-band waveguide filters, together with a *Ka*-band orthonormal mode transducer (OMT), are presented as examples.

II. ADVANTAGES AND CHALLENGES OF 3-D PRINTING MICROWAVE WAVEGUIDE DEVICES

Compared with conventional computer-numerical-control (CNC) milling, 3-D printing offers appealing advantages. Firstly, fabrication cost can be significantly reduced for devices with complicated geometries, such as the filter based on spherical resonators [4], since the cost of 3-D printing mainly depends on the device's volume instead of its structural complexity. Such great geometrical flexibility offered by 3-D printing also enables new designs with enhanced performance (e.g., [4]). Secondly, nonmetallic materials (e.g., acrylonitrile-butadiene-styrene plastic in [1] and the polymer resin in [4]) could be utilized to construct devices with much lighter weights, and such devices are attractive for applications in satellite or aerospace communication systems. Additionally, most materials outside of the

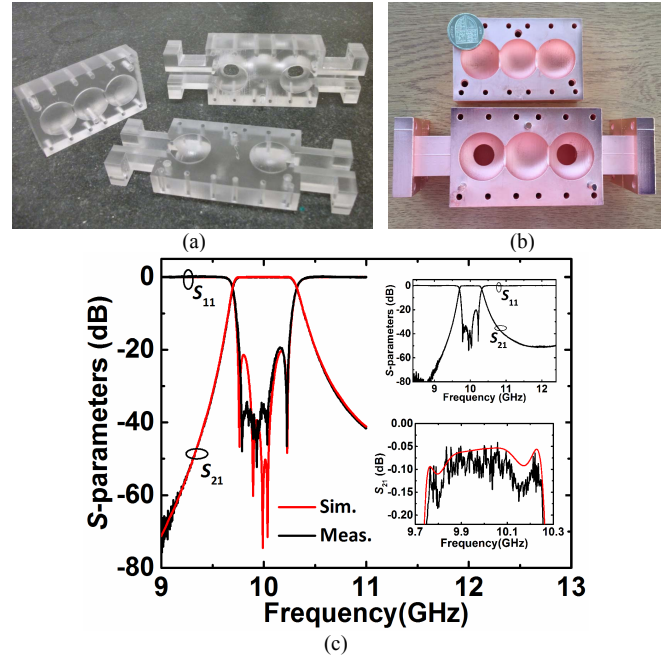


Fig. 1. A 3-D printed *X*-band fifth-order waveguide BPF based on spherical resonators. Photographs of (a) as-printed and (b) copper-plated building blocks of the filter. (c) Simulated and measured frequency responses [4].

printed devices can be removed to reduce their weights further.

Stereolithography (SLA)-based 3-D printing uses laser beam for solidification and provides a resolution of 25–50 μm and a surface roughness of $\sim 1 \mu\text{m}$. Such geometrical accuracies are satisfactory for most *X*-band devices and some *W*-band devices. However, there are challenges to be tackled before widespread application of 3-D printed microwave waveguide devices. The first issue lies in the difficulty in precisely controlling of the metal-coating thickness on the inner surfaces during the plating process. A uniform metal layer is difficult to achieve on the internal surface of the device. This may change internal dimensions of the devices, which ultimately degrades their performance in particular for those operating at higher frequencies [1]. Usually, devices need to be printed into more than one pieces in order to gain access to inner surfaces during plating process. This may cause other problems such as joining. Poor heat-performance of the nonmetallic material is another weakness which needs to be mentioned. The material we used here has a working temperature of no more than $\sim 40^\circ\text{C}$, which limits power-handling capability and application environment of the device. Ceramic-filled resin with a working temperature of 120–250 $^\circ\text{C}$ can be used as a solution. As another alternative

approach, metal 3-D printing without the need of metal-plating process can be used. However, it comes with a larger surface roughness (e.g., $\sim 6 \mu\text{m}$ as reported in [2]). Polishing could be used to reduce the roughness but cannot be easily done especially for inner surfaces.

III. 3-D PRINTED WAVEGUIDE DEVICES

SLA is adopted to fabricate devices in our work. Polymer resin was solidified layer by layer by using laser to build the blocks, which was followed by a metal plating process for surface metallization. These devices were made by 3D Parts and Swissto12.

A. An X-band BPF Based on Spherical Cavity Resonators

The 3-D printed X-band fifth-order BPF in [4], as illustrated in Fig. 1(a) and (b), exemplifies the SLA technique for printing high quality factor (Q) spherical cavity resonators which are difficult to make using CNC milling. This filter is printed into three pieces to ease the metallization (25- μm thick copper) of its internal surfaces, and it is 85% lighter than that made from copper. The filter exhibits an ultra-low passband insertion loss of $\sim 0.1 \text{ dB}$, as shown in Fig. 1(c).

B. An X-band BPF Based on Spherical Dual-Mode Resonators

A 3-D printed X-band fourth-order BPF based on spherical dual-mode resonators is shown in Fig. 2(a). This filter shares the same coupling topology to the ones in [5], where the dual-mode spherical resonators are arranged in-line to ease the copper-plating process. Holes and slots are adopted to the resonator and waveguide surfaces, which further eases the plating process (offers easy access for the plating solution into the cavities) and additionally reduces the filter weight without the penalty of degrading the resonator's Q .

C. A Ka-band OMT

A Ka-band OMT, as shown in Fig. 2 (b), is also fabricated using SLA-based 3-D printing at 3D Parts. The OMT is designed to operate at two frequency bands, with each band passing an orthogonal polarization. It is part of the transmitter/receiver feed chain components of a satellite communication system, and such system desires a compact size and a reduced weight. To facilitate the plating process, the OMT has been printed into two pieces, as shown in Fig. 2 (b). These two pieces are assembled using screws and pins. The OMT's measured responses have a good agreement with the simulated ones.

D. W-band Waveguide BPFs

The size of waveguide shrinks with increasing frequencies. 3-D printing has been utilized to produce two W-band BPFs. The photographs of these two filters are shown in Fig. 3. The first BPF (Fig. 3(a)) is centered at 100 GHz, based on a single piece, and includes features with high aspect ratios. Fig. 3(b) shows another W-band BPF operating at 90 GHz, incorporating slots on both narrow-side and broad-side walls to facilitate the plating process. These slots are specially

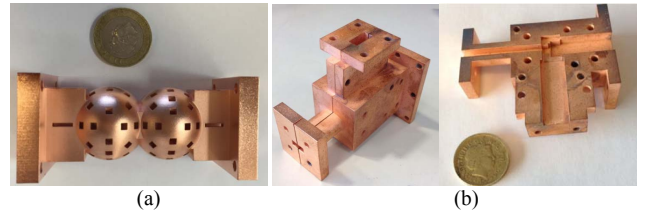


Fig. 2. Photographs of (a) a 3-D printed X-band BPF based on spherical dual-mode resonators and (b) a 3-D printed Ka-band OMT (left: the entire OMT structure; right: half of the OMT). All device surfaces were copper plated.

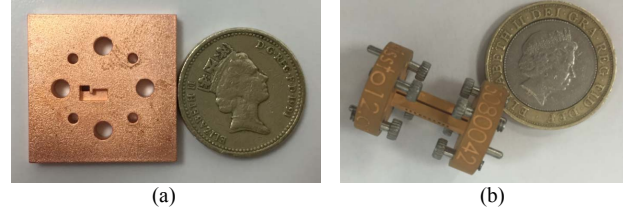


Fig. 3. Photographs of 3-D printed W-band waveguide BPFs (after copper plating). (a) Fourth-order filter made by 3D Parts. (b) Fifth-order filter fabricated by Swissto12.

designed to avoid radiation [6]. Neither of these two filter designs can be easily fabricated using conventional CNC milling. This demonstrates the great flexibility of 3-D printing technique. Both filters have been tested and results will be shown in the meeting.

IV. CONCLUSION

A range of waveguide passive circuits have been demonstrated using 3-D printing up to W-band. The polymer-based circuits offer a significant reduction in weight, which is highly desirable for some applications. The accuracy of the 3-D printing process also allows excellent responses which are comparable to that of metal ones to be produced. This demonstrates the great potentials of 3-D printing for the small to medium batch size manufacturing of microwave waveguide circuits.

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